GOVERNMENT OF MALAWI

MINISTRY OF AGRICULTURE, IRRIGATION AND WATER DEVELOPMENT

SHIRE VALLEY IRRIGATION PROJECT

Hydraulic Modelling of Intake

Data exploration report

28th September 2016

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TABLE OF CONTENTS

FIGURES

TABLES

1. INTRODUCTION

1.1. THE SHIRE VALLEY IRRIGATION PROJECT

Since the 1960s, Government of Malawi (GoM) has been interested in the implementation of Shire Valley Irrigation Project (SVIP) to develop irrigation in the Lower Shire Valley. Since then, the proposed project has been the subject of a large number of surveys and studies.

The GoM has requested financial assistance from the World Bank (WB) and the African Water Facility (AWF)/ African Development Bank (AfDB) for the preparation of the SVIP. Accordingly, the WB and AfDB are supporting the GoM with the preparation of comprehensive studies required to appraise the technical feasibility, economic/financial viability, environmental and social sustainability of the SVIP

Fig. 1. Shire River Basin

The SVIP is proposed to irrigate about 42,500 ha of land in the southern part of Malawi within the administrative districts of Chikwawa and Nsanje. The irrigable area is located on the west (right) bank of the Shire River in the Lower Shire River Valley (on the south of Shire River Basin, see Fig. 1). The intake of SVIP is proposed to be located upstream of Kapichira Dam[1].

1.2. PROJECT OBJECTIVES OF THIS STUDY

It is proposed to locate the SVIP intake upstream of Kapichira dam. As the introduction of an intake structure close to the Kapichira dam could have an adverse impact mainly on the reservoir

[1] Exact site to be determined by the present study.

sedimentation pattern and consequently on the concentration of sediment in the power plant intake and on the operation of the dam, it is of paramount importance to properly analyze the hydraulic behaviour around these structures under the various proposed configurations of the SVIP intake structure with various operational scenarios of the Kapichira dam. Furthermore the location of the SVIP intake could also have an impact on the suspended sediment concentration entering the SVIP main canal.

Consequently, it has been proposed by the Client, the AfDB and the WB to conduct a 3D mathematical modeling of the Shire river and Kapichira reservoir, including the existing power plant intake and the future SVIP intake to solve the problems related with the dynamics of sediment transport and river (reservoir area) morphology.

The objectives of the study are:

- to use the preliminary design of the intake general location and range of design discharges provided by the feasibility consultants, recommend the optimum site of the intake structure;
- to study the likely impacts of introducing the SVIP intake structure on the hydraulic behavior (incl. sedimentation) in the head-pond area and around the intake to iteratively determine the most optimal and efficient sediment exclusion and/or sediment ejection works to ensure safety and operational flexibility e at the SVIP intakeand Kapichira Power intakes. The scenarios considered in the iterative simulation exercise and the recommendations thereof should clearly demnostrate that the introduction of the SVIP intake structure and diversion of water to the feeder canal does not significantly affect the hydraulic performance of the two headworks;
- to study the reservoir sedimentation behaviour under various combination of the SVIP intake and Kapichira dam operations on the flushing regime and propose the appropraite modifications to ensure efficient flushing regime as determined by the hydraulic model simulation results; and
- to provide necessary guidance (feedback) based on the above objectives and findings as input to the Detail Design and other related studies of the SVIP.

To meet these requirements, various tasks have to be carried out during this study, mainly:

- hydrological and sedimentological data collection
- site visit
- meeting with the stakeholders
- meeting with other Consultants of the SVIP (mainly the Technical Feasibility consultancy)
- bathymetric campaign in the reservoir
- sedimentological campaigns (suspended sediment and bedload sediment)
- construction of 3D hydraulic and sedimentological numerical model of the reservoir and intakes
- tests of various intake locations and reservoir operations

1.3. PURPOSE OF THE REPORT

The purpose of this data Exploration Report is to present:

- a first analysis of the data collected,
- the undertaking and the results of the bathymetric survey,
- the undertaking and the results of the sediment survey,

2. HYDROLOGY

2.1. DATA

Four datasets have been provided by ESCOM:

1) Daily river discharge at station 1B1 (Liwonde station) from 2006 to 2016;

2) Daily spillway discharge of Kapichira dam from 2000 to 2016;

3) Daily headpond water levels at Kapichira from 2014 to 2016;

4) Spillway discharge and headpond water level from 19/03/2015 to 27/12/2015 at a 30 minutes time-step.

Data have been processed (see Inception Report for details) to correct errors and facilitate the analysis.

As daily flow at Liwonde before 2006 is not known in this dataset, monthly flow at Liwonde between 2000 and 2006 have been retrieved in an Excel file accompanying the report "*Water Resources Investment Strategy - Component 1 – Water Resources Assessment"* written in April 2011 by WS Atkins International Ltd in association with Wellfield Consulting Services (Pty) Ltd and Interconsult Malawi for the Government of the Republic of Malawi - Ministry of Irrigation and Water Development - Second National Water Development Project (NWDP II)

Numerous reports have presented information about the hydrology of the Shire River. Of particular interest are the 2001 report by Atkins called "Water Availability on the Shire River at Kapichira Dam for the proposed Shire Valley Irrigation Project" and the 2013 Report by Norplan called "Water Availability for Irrigation and Hydropower Production on Shire River at Kapichira Falls", which both give an assessment of the water availability for SVIP and hydro power development. In both report some information about incremental discharge between Liwonde and Kapichira can be found. This information is of particular interest for building time-series of discharge at Kapichira (see 2.3).

2.2. DISCHARGE THROUGH TURBINES

The time-series of discharge through the turbines are not known. According to ESCOM, the power plant tends to operate at full capacity, although there are some moments during the day of peak demand (morning and evening) and moments of lower demand (night). ESCOM did not have records of actual discharge through the turbines to provide us.

The operating discharge of the turbines is according to ESCOM of 260 m^3/s since 2014, and of 130 m^3/s previously, when only two turbines were operated.

In order to appreciate the daily variation of discharge through the turbines, an estimation of this discharge is computed by performing a volume balance of the reservoir using the data on water level in the reservoir (that gives us an estimation of the volume of water in the reservoir), data on incoming flow and data on outgoing flow through the spillway.

As indicated in the previous paragraph, we have knowledge of discharge entering the reservoir during dry season, when incremental discharge between Liwonde and Kapichira is negligible. In that case, the incoming discharge is indeed equal to the discharge from Liwonde dam, as the dams of Nkula Power Station and Tedzani Power Station have no storage and thus do not modify the incoming flow.

We also have knowledge of spillway discharge and water level in the reservoir at a 30 minutes time step from 19/03/2015 to 27/12/2015.

As this period roughly corresponds to dry season, incoming flow in the reservoir can be considered equal to flow from Liwonde dam. All terms of the volume balance of water in the reservoir are thus known, except the discharge through the turbines, which can therefore be computed. The computed discharge through the time period is then averaged to draw a representative daily variation of discharge. It is shown on the figure below.

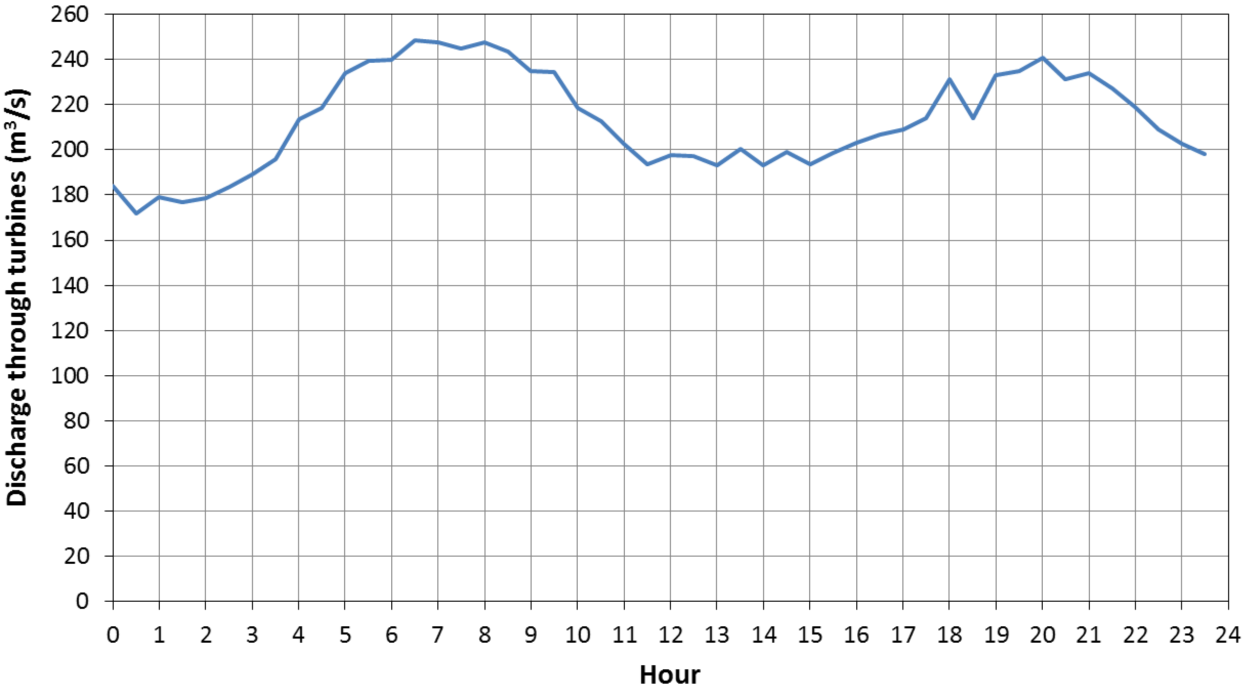

Fig. 2. Average daily variation of discharge through the turbines

This work confirms that there is a daily pattern for discharge through the turbines, with slightly lower discharges at night.

The average discharge through the turbines during the period is 213 m^3/s.

2.3. HYDROLOGIC SCENARIO FOR LONG-TERM CALIBRATION

Long term calibration of the model consists in simulating the whole period of existence of the dam (from 2001 to 2016), and comparing the simulated sediment deposits to the observed deposits.

The hydrologic scenario (incoming and outgoing flows, water level in the reservoir) for this calibration period will be as close to possible as the reality.

The data available presented before, as well as the assumptions about discharges at the dam presented below, enable to build a full chronic of discharges both for inflow and outflows.

The incremental discharge between Liwonde and Kapichira during the dry season needs to be estimated in order to build this chronic. In the 2013 report by Norplan, incremental discharge is estimated in paragraph “5.4 The Tributaries”. It is estimated at 50.9 m^3/s as a yearly average. The incremental discharge during the dry season is not estimated by the study, but results from Lahmeyer International/Knight Piésold (1998) are presented, which indicate an incremental discharge during the dry season that remains below 10 m^3/s. Another estimate (this time between

Liwonde and Chikwawa) is presented in the 2011 report by Atkins, in the paragraph "2.3. River Shire flows at Chikwawa (1L12)". The average incremental discharge is estimated at 14.3 m^3/s for July and August, and at -3.5 m^3/s for September to November. It is even mentioned in this report "during the dry season, flows at Chikwawa tend to be very similar to, or slightly less than flows at Liwonde". The incremental discharge between Liwonde and Kapichira will thus be considered negligible (set to zero) during the dry season.

Furthermore, the discharge at Liwonde before 2006 is only known at a monthly time-step, while a daily time-step is used in the time-series we build. The error generated is very small as monthly variation of daily discharge at Liwonde is very small during the dry season, and the data at Liwonde is only used for the dry season.

The chronic for inflow discharge is built thus:

- in the dry season (June to October included), inflow discharge is equal to the measured discharge at Liwonde;
- in the rainy season, inflow discharge is equal to the measured spillway discharge plus the estimated discharge through the turbines (128 m^3/s before 2014, 256 m^3/s after).

The figure below presents the whole chronic.

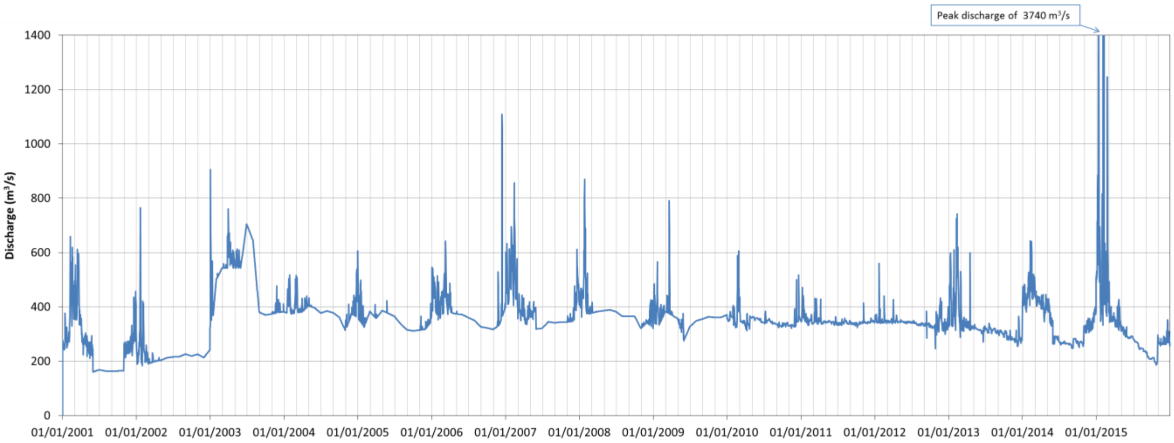

Fig. 3. Inflow discharge in Kapichira reservoir

The hypotheses about management of discharge at the dams are the following:

- Environmental flow : 17 m^3/s
- Discharge through the turbines 128 m^3/s for 2001-2013, 256 m^3/s for 20014-2015;

The water level in the reservoir will be regulated at a fixed value of 146.5 m.

The flushings during this period will be taken into account according to the data we have on the flushings of the period from 19/03/2015 to 27/12/2015 (described by spillway discharges and water level in the reservoir at a 30 minutes time-step). Based on this, we will use the following hypothesis for the flushings:

- Frequency: every two months
- duration: eight hours
- water level in the reservoir during the flushing : 142.9 m

3. TOPOGRAPHY AND BATHYMETRY

3.1. EXISTING DATA

The existing data is the following:

- map of the topography of the river valley before the dam
- plans of the dam that include detailed topography of the reservoir

These maps have been digitized and georeferenced

3.2. BATHYMETRIC CAMPAIGN

The bathymetric campaign was performed by two employees of SINTEGRA (subcontractor of ARTELIA Eau & Environnement) during the period from 5 to 12 April 2016.

The wooden boat from Majete Park was rented, and a Tritech PA500 Single Beam Echosounder was mounted on it. A couple of GNSS receivers (ASHTECH SPECTRA PM800) were used for georeferencing.

The survey consisted in transverse and longitudinal profiles covering the reservoir. The bathymetric transverse profiles were completed by topographic survey of the bank of about 10 meters long.

The hydrodynamic conditions did not allow covering the whole reservoir:

- water height was too low in the side banks to enable navigation;
- because of the presence of rocky shoals, navigation was too dangerous in some channels, that were therefore not covered;
- ESCOM asked for safety reasons not to survey the part of the reservoir directly upstream of the spillways (length of the non-covered area: about 120 m).

Fig. 4. **Location of bathymetric survey profiles**

A first view of the bathymetric results is presented in annex 1

3.3. ANALYSIS

The data presented above has been used to build two Digital Terrain Models (DTM), which in turn provide the basis for the bathymetry of the numerical model.

- The first DTM consists in the bathymetry of the reservoir including the dam in its initial state, just after the completion the dam and thus without any sediment deposits.
- The second DTM consists in the bathymetry of the reservoir including the dam in its present state.

For both DTM, the data does not cover the full extent of the reservoir and some assumptions have had to be made:

For the initial state, the detailed topography that is included in the plans (topographic data from 2001 or before) of the dam does not cover the upstream part of the reservoir. The assumption has been made than in the upstream part of the reservoir (where the river bed is separated in different channels by the islands), the sediment deposits are negligible. Thus, the 2016 bathymetry is used for the initial state in that upstream part of the reservoir. An interpolation along contour lines (drawn following the channels) has been performed between the two datasets (2001 and 2016) to ensure a smooth transition between the upstream part of the reservoir and the downstream part that is covered by the 2001 data.

For the present state, the area just upstream of the dam (distance of about 120 meters) has not been covered for safety reasons. As ESCOM performs flushing regularly, one expects this area to be relatively free of sediment deposits. Therefore the topographic data from the plans of the dam have been used for this area.

These two DTMS are presented in the figures below.

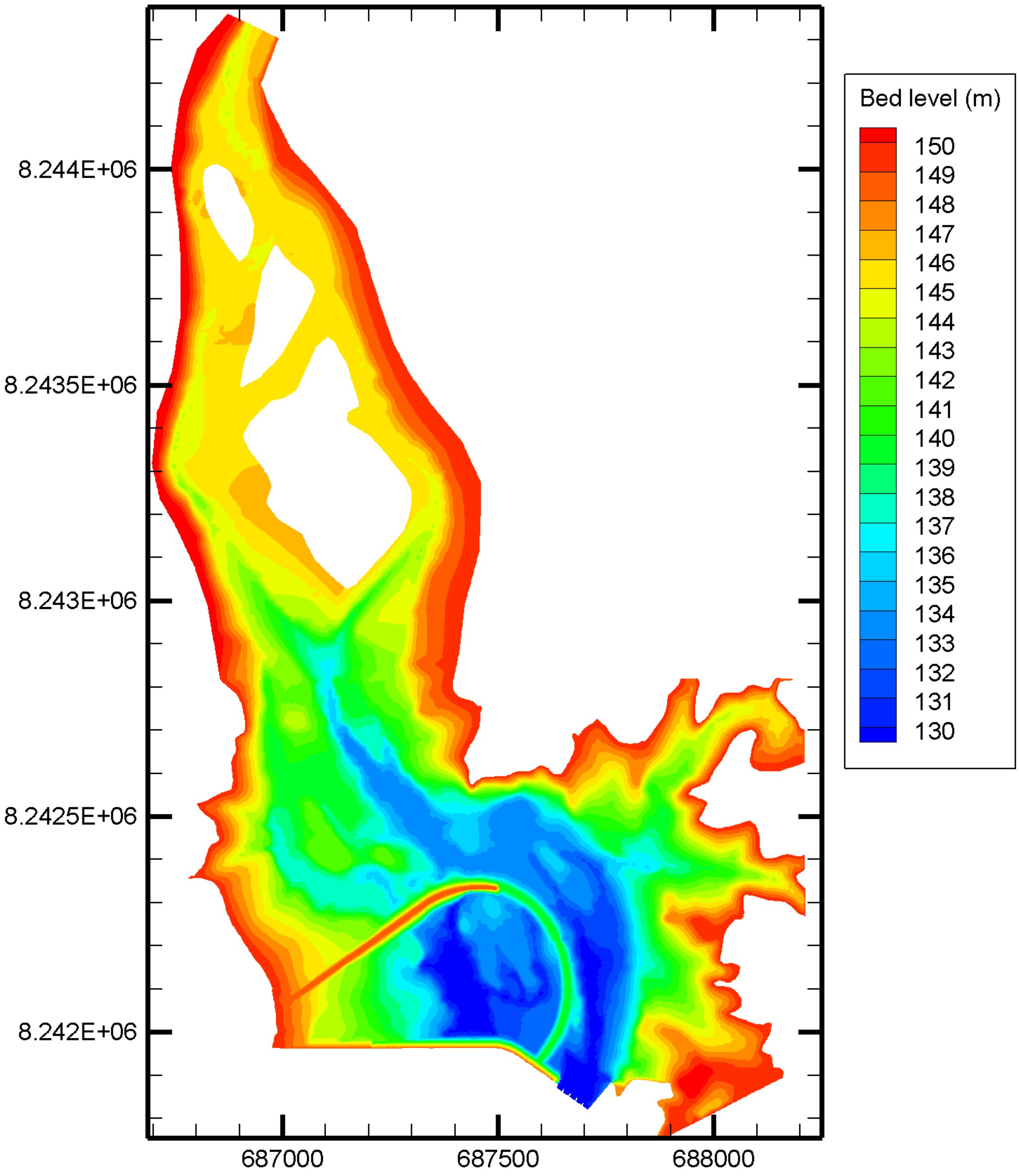

Fig. 5. Digital Terrain Model – Initial Bathymetry

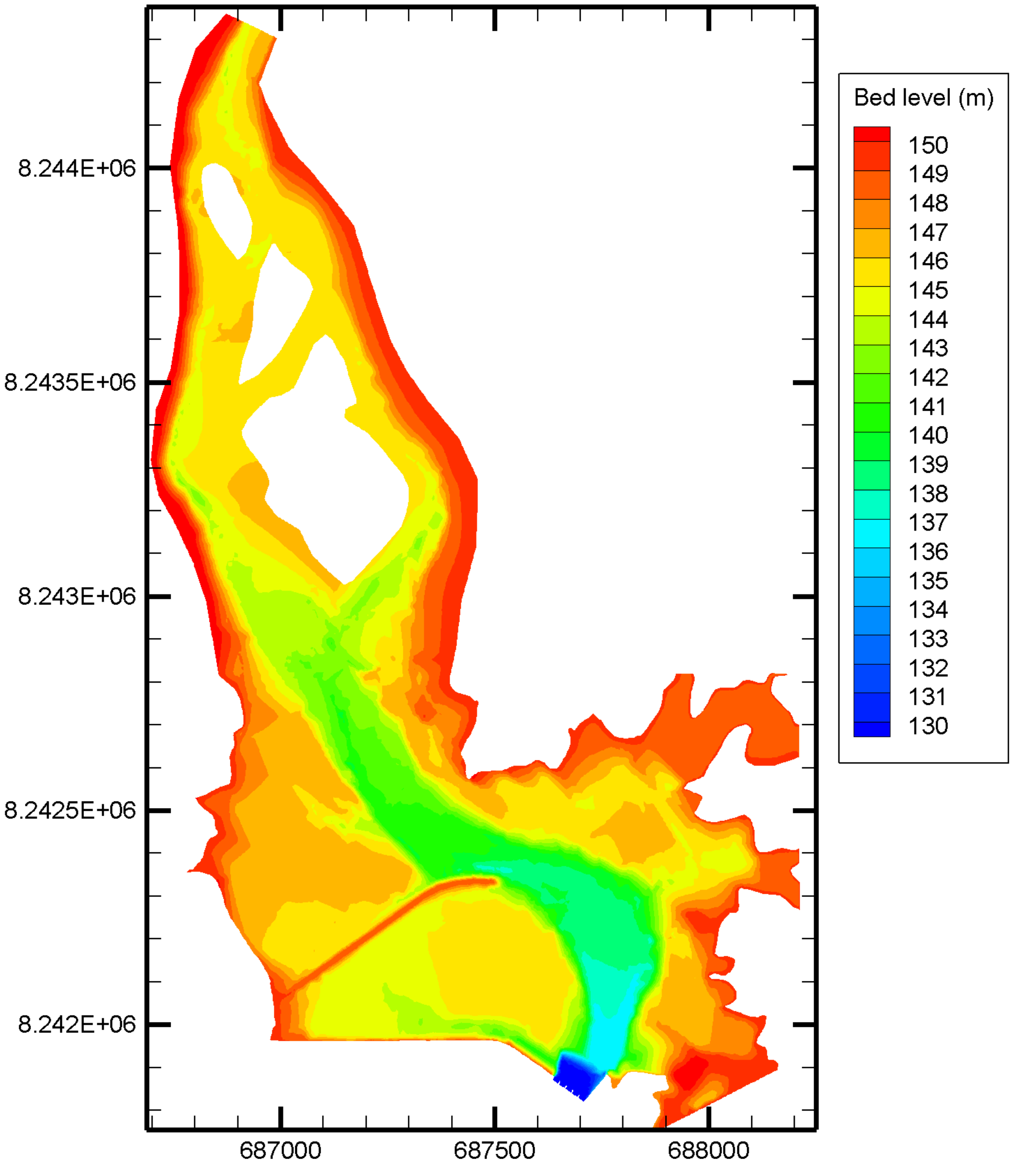

Fig. 6. Digital Terrain Model – 2016 bathymetry

The volume of sediment deposited in the reservoir since the building of the dam can be computed from the differential of the two DTM. The estimated value is of 4 700 000 m^3.

The map of the differential of the two DTM, which gives the thickness of the sediment deposits, is presented in the figure below.

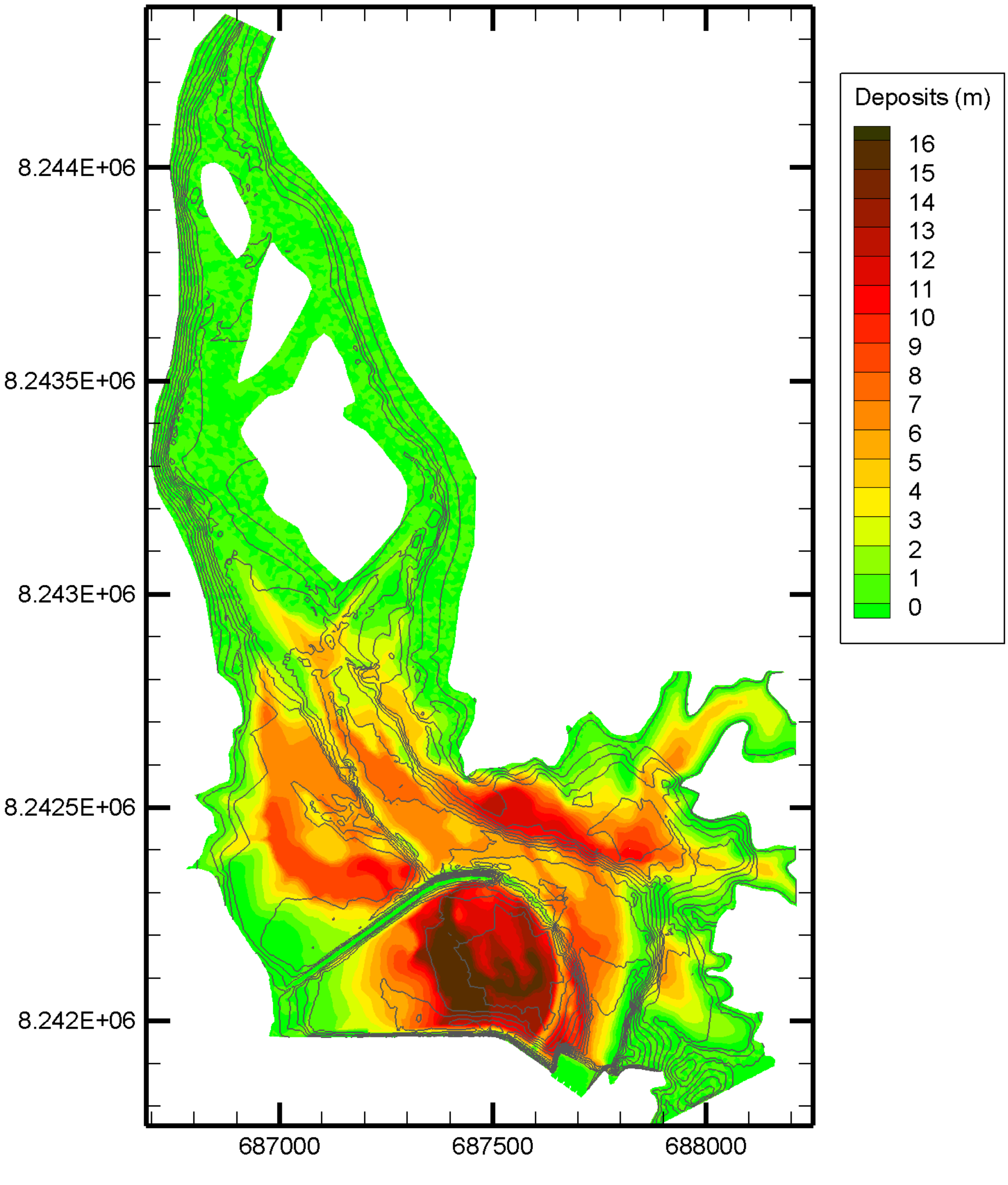

Fig. 7. Thickness of sediment deposits since the building of the dam

4. SEDIMENT IN SUSPENSION

4.1. EXISTING DATA

The report from 2006 by CODA and Partners for Government of Malawi mentions: *"In 1991, ESCOM carried out sediment load analysis on the river. The results showed concentrations of between 50mg/l and 1800mg/l"*

There are slightly more details on these measurements in a report found in the archives of ARTELIA. This report is: SOGREAH-BCEOM (1992). *Lower Shire Valley Irrigation Development Project* - Detailed Design Study – Final Report – Appendix 2 – Hydrological study. This report mentions:

"Analyses of suspended load carried out by ESCOM in January and February 1991 show concentrations of between 50 and 1800 mg/l. If three measurement periods are omitted, that is, 4 - 8 January, 17 -18 January and 12 February, since they probably correspond to flood periods in the intermediate basin (values vary from 0.9 g/1 to 1.8 g/l), suspended load outside flood periods can be estimated at 0.2 g/l for the period in question. Suspended load would thus appear to be much greater than it was in 1957. It is certain that deforestation has increased soil erosion, and if action is not taken to stop this process, the situation may become worse. It therefore seems reasonable to assume that suspended load is of the order of 0.3 g/l, and could be as high as 2 g/l during floods."

4.2. SAMPLING CAMPAIGNS

4.2.1. Schedule

The first sediment sampling survey took place on 1st and 2nd of April 2016, and was performed by employees from Malawi Polytechnic, with the help of Ruo Consultants. We received the results from the laboratory analysis for the first campaign the 4th of May.

The second sedimentological field campaign has taken place on 26 and 27 of May 2016. We received the results from the laboratory analysis for the second campaign the 20th of July.

4.2.2. Equipment used

A Wildco bottle (a kind of Niskin bottle) is used for sampling of sediment in suspension.
It consists in a tube with plugs on both ends (see picture below).

Fig. 8. Sampling bottle

The functioning of this sampling device is the following: the plugs are opened, and the bottle is attached with a rope and lowered in the water. When it reaches the desired depth, a "messenger" weight is sent down the rope, which enables to close the bottle. The bottle is then taken out of the water and the sample is collected.

As the samples in the reservoir were taken from a boat, the velocity of the flow is zero compared to the bottle (the boat is drifting when the sample is taken). The Niskin bottle is therefore vertical (or nearly) during the sample, as must be (see for instance Rijn, L. C. van (1986). *Manual sediment transport measurements*. Delft, The Netherlands: Delft Hydraulics Laboratory, a summary of which is presented here: *http://www.coastalwiki.org/wiki/Bottle_and_trap_samplers*). The sample is thus truly representative, despite the strong currents. This criterion of zero relative velocity is not respected for sampling downstream of the dam, but given the excellent mixing there, we expect the sample to be representative as well.

All samples are then filtered, dried and weighted in order to determine the suspension sediment concentration.

4.2.3. Sampling location

The location of the samples of sediment in suspension for the first sediment survey is presented in the figure below. For each location, there are two samples of different depth (for instance samples S_1 and S_2 were taken at the same location but at different depths).

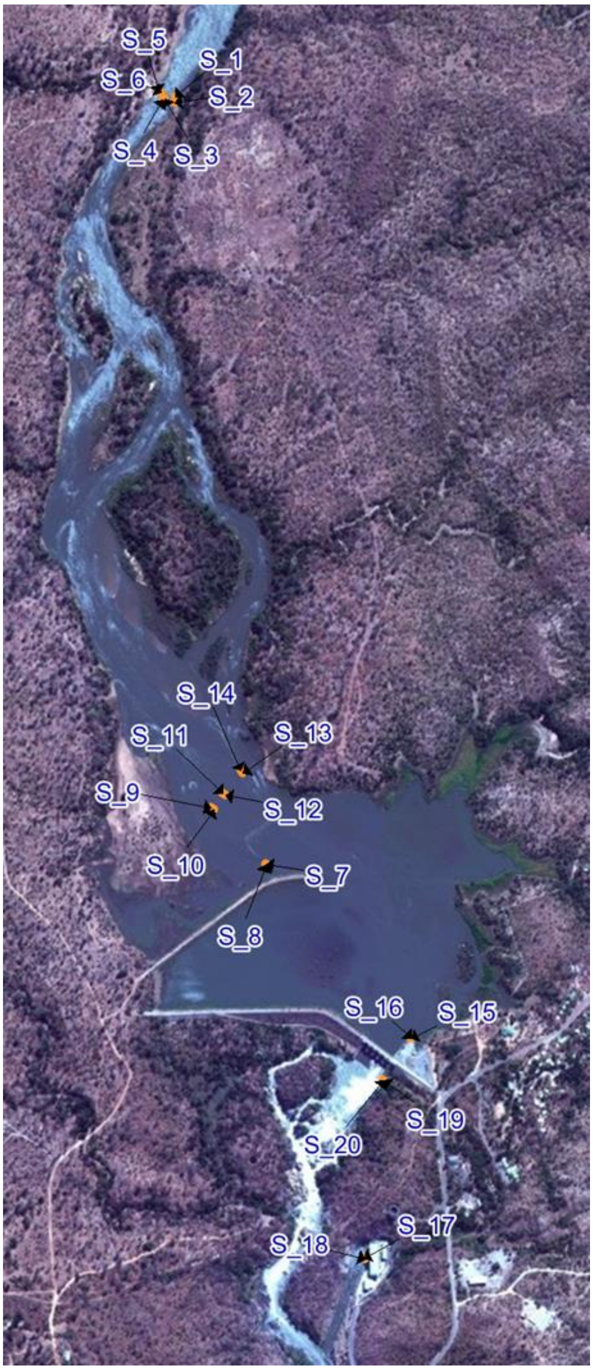

Fig. 9. Location of suspended sediment samples – first sediment survey

The location of the samples of sediment in suspension for the second sediment survey is presented in the figure below. The samples took place during two days. The samples noted “S” were taken the 26 of May 2016 while the samples noted “SS” were taken the 27 of May 2016.

Fig. 10. Location of suspended sediment samples – second sediment survey

4.2.4. Results

The following table presents the results in terms of concentration of sediment in suspension for the first survey. The depth under water level at which each sample was taken is also displayed.

Tabl. 1 - Results of suspended sediment samples – First Campaign

SAMPLE NUMBER (POINT NAME)	POINT DESCRIPTION	DEPTH (m)	SUSPENDED SEDIMENT CONCENTRATION (mg/L)
S_1	Upstream - Left	1.0	156
S_2	Upstream - Left	1.2	288
S_3	Upstream - Centre	1.0	92
S_4	Upstream - Centre	2.0	411
S_5	Upstream - Right	1.0	272
S_6	Upstream - Right	2.2	227
S_7	Spur Dyke - Upstream side	1.0	108
S_8	Spur Dyke - Upstream side	4.5	127
S_9	Middle of reservoir - Right	1.0	131
S_10	Middle of reservoir - Right	5.5	127
S_11	Middle of reservoir - Centre	1.0	92
S_12	Middle of reservoir - Centre	4.4	97
S_13	Middle of reservoir - Left	1.0	60
S_14	Middle of reservoir - Left	3.8	105
S_15	At ESCOM Intake	1.0	122
S_16	At ESCOM Intake	2.0	147
S_17	Downstream ESCOM plant	1.0	149
S_18	Downstream ESCOM plant	2.5	122
S_19	At ESCOM Spillway	1.0	149
S_20	At ESCOM Spillway	2.0	183

The following table presents the results in terms of concentration of sediment in suspension for the second survey.

Tabl. 2 - Results of suspended sediment samples – Second Campaign

SAMPLE NUMBER (POINT NAME)	POINT DESCRIPTION	DEPTH (m)	Date (May 2016)	SUSPENDED SEDIMENT CONCENTRATION (mg/L)
S_1	Upstream - Left	1	26	48
S_2	Upstream - Left	1.56	26	59
S_3	Upstream - Centre	1	26	54
S_4	Upstream - Centre	2.56	26	47
S_5	Upstream - Right	1	26	57
S_6	Upstream - Right	1	26	65

S_7	Entrance of reservoir - left	1	26	78
S_8	Entrance of reservoir - left	2	26	69
S_9	Middle of reservoir	1	26	63
S_10	Middle of reservoir	6	26	89
SS_1	Upstream - Left	1	27	42
SS_2	Upstream - Left	2.6	27	51
SS_3	Upstream - Centre	1	27	49
SS_4	Upstream - Centre	3.8	27	43
SS_5	Upstream - Right	1	27	57
SS_6	Upstream - Right	1.5	27	62
SS_7	Entrance of reservoir - left	1	27	67
SS_8	Entrance of reservoir - left	3.6	27	71
SS_9	Middle of reservoir	1	27	65
SS_10	Middle of reservoir	6.48	27	84
SS_17	Downstream ESCOM plant	1	27	57
SS_18	Downstream ESCOM plant	5	27	56

4.3. ANALYSIS

The concentrations measured during the first campaign (1st of April) are much larger that the concentrations from the second campaign (26 and 27 of May). It indicates a strong decrease of the suspended sediment concentration at the end of the rainy seasons. According to African Parks at Majete, the turbidity of the water decreases during the dry season, and the water is clear at the end of the dry season. Thus, as May is the beginning of the dry season, a further decrease of suspended sediment concentrations can be expected during the dry season.

In general, for both campaigns, the concentrations at a same location but different depth are close to each other, which show that the vertical stratification of sediment in suspension is weak. For the first campaign, two of the upstream points are exceptions to this trend: the left and centre upstream points indeed show a strong stratification. This could indicate that sediment in suspension in this area is coarser that in the reservoir downstream.

The results from the first campaign show a decrease of concentration of sediment in suspension between the upstream end of the reservoir (average concentration of 240 g/l) and the middle of the reservoir (average concentration of 100 g/l). Between the middle and the end of the reservoir, there seems to be no decrease of concentration in suspension.

The results from the second campaign do not show a decrease of concentration in the reservoir, which indicates that there is very little settling of sediment in the reservoir during that time.

The value of suspended sediment concentration entering the reservoir during the first survey is of about 0.25 g/l, which is consistent with the literature which mentions a value of suspended load during the rainy season (but outside floods) of about 0.3 g/l.

These data will be used to build time-series of sediment concentration entering the reservoir for the numerical modelling

5. BED SEDIMENT

5.1. EXISTING DATA

A granulometric survey of sediments from reservoirs in the Middle Shire River (Kapichira, Nkula and Tedzani) had already been performed and is described in the 2011 report named *Malawi Power System Project Studies - Revised Final Feasibility Study Report - Annex 7: Sediment (Silt) Management Assessment Report* prepared by ICF International and CORE International, Inc. for the Millenium Challenge Corporation.

Most samples were taken in Nkula reservoir, with one sample in Tedzani reservoir and one sample in Kapichira.

The data is presented in the following figure.

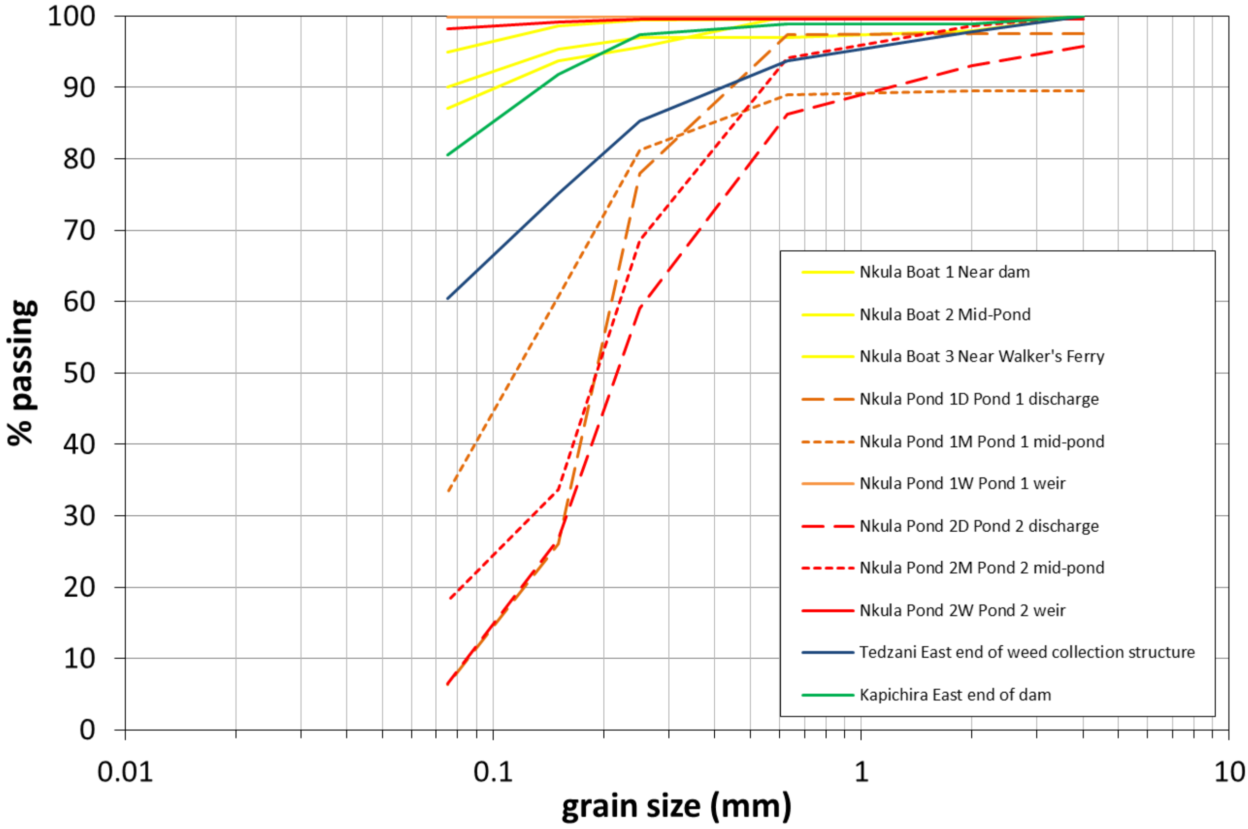

Fig. 11. Granulometric data from MCC (2011)

The representative grain size of the sand in Nkula reservoir is about 0.2 mm. This is not very precise as the interval between the sieve sizes was quite large.

The authors of the study wrote in the fore-mentioned report the following comments concerning the grain size analysis:

"As expected, the sieve analysis of the samples taken from the head ponds indicated that the particle size distribution was mostly silt. This is because the samples that were taken from near shore will probably only contain silt, as the flow patterns are such that the sand fraction has already dropped from suspension because of the low water velocity at these locations. The samples taken from Nkula off the boat similarly contained mostly silt, as it has been shown that much of the sediment load in the reservoir exhibits stratification, with the sandy fraction on the bottom and the silt fraction above (Exhibit 2). It was not possible using the technique employed (pipe sampling) to obtain samples from deep enough in the sediment profile to recover the entire column of sediment. The particle size distribution of samples recovered from the two Nkula disposal areas show that sandy material is located near the discharge point, intermediate particles at the mid-pond location, and almost all silt at the weir. These results are as expected given the flow characteristics of the dredge discharge stream. It is also noteworthy that there is only a small fraction of pebble-size material even in the "sandy" portion near the discharge. This corroborates other information (Dredger Specifications—see Section 1.4.1—and site personnel comments) that suggests that the sediment load is mostly sand and silt."

These data, though very instructive, are not sufficient to properly characterize sedimentation in Kapichira reservoir and to set up parameters for the numerical models. The new sampling campaigns performed recently and presented here address the missing information from the previous campaign.

5.2. SAMPLING CAMPAIGNS

5.2.1. Program

The first sediment sampling survey took place on 1st and 2nd of April 2016, and was performed by employees from Malawi Polytechnic, with the help of Ruo Consultants. We received the results from the laboratory analysis for the first campaign the 4th of May.

The second sedimentological field campaign has taken place on 26 and 27 of May 2016. We have received the results on 20th of July.

5.2.2. Equipment used

A Van Veen Grab Sampler is used to sample sediment from the bed. A picture of it is presented below.

Fig. 12. Van Veen grab

While letting the instrument down into the water, the two levers with buckets at their ends are spread like an open scissor. The levers are locked in this position, and unlock when hitting the ground. When the rope is pulled upward again, the two buckets close and grab a sediment sample from the bed.

5.2.3. Location of samples and results

The figures below present the location of the bedload samples. The colours of the pie charts are defined in the following way:

Yellow: sand, grain diameter > 63 microns
Red: clay and silt, grain diameter < 63 microns

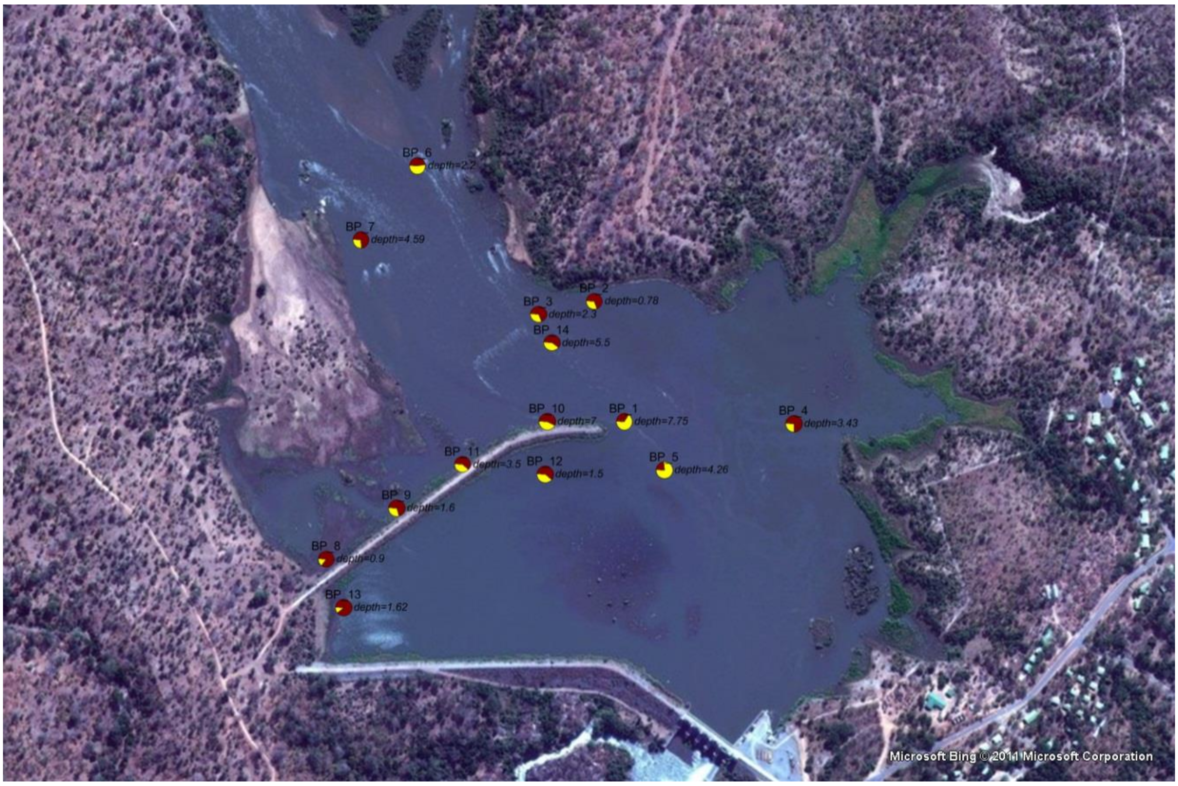

Fig. 13. Location and size-classes distribution of bedload samples – first survey

Fig. 14. Location and size-classes distribution of bedload samples – second survey – upstream of the reservoir

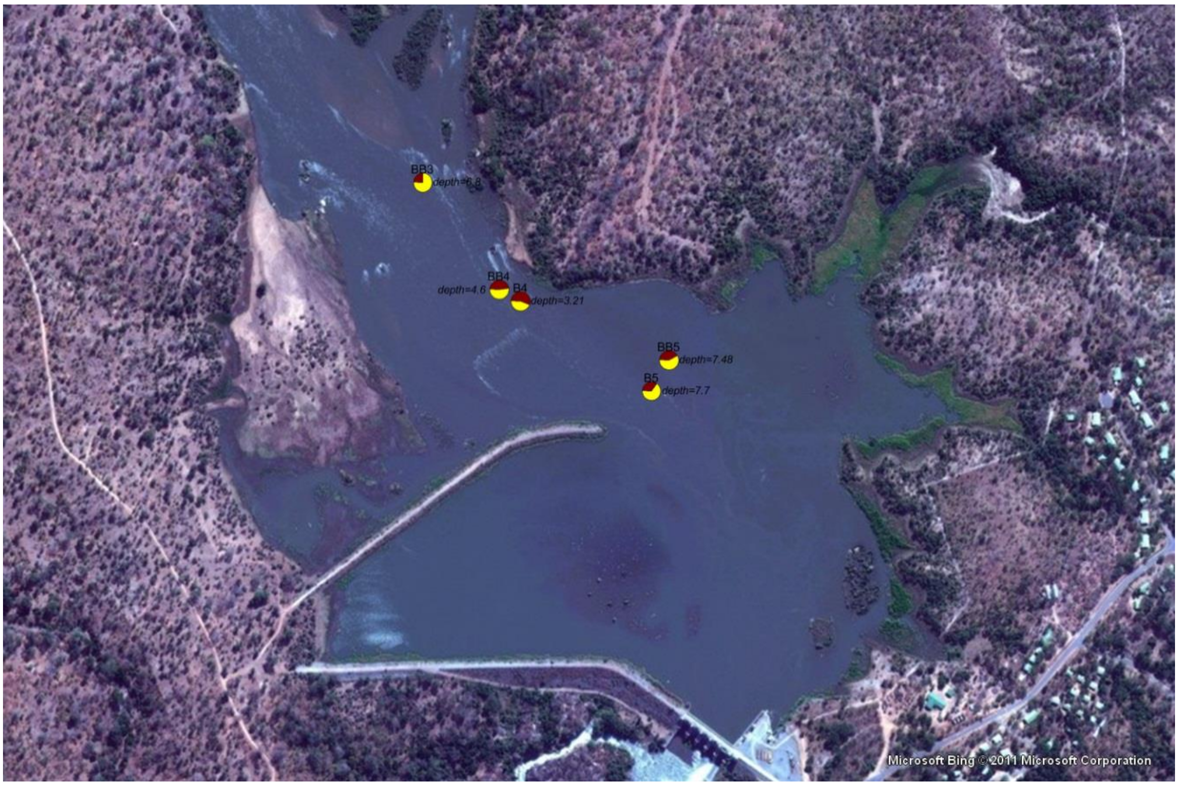

Fig. 15. Location and size-classes distribution of bedload samples – second survey – middle of the reservoir

The tables below present more information for each sample. The median diameter (D_{50}) that is reported is the one of for sand, i.e. the sediment finer than 63 microns is not taken into account for its determination.

Tabl. 3 - Results of bed load samples – First Campaign

SAMPLE NUMBER	DEPTH (m)	clay and silt (%)	sand (%)	D_{50} OF SAND FRACTION (mm)
BP_1	7.75	34.7	65.3	0.17
BP_2	0.78	69.3	30.7	0.12
BP_3	2.3	68.7	31.3	0.11
BP_4	3.43	74.1	25.9	0.16
BP_5	4.26	24.6	75.4	0.12
BP_6	2.2	48.1	51.9	0.17
BP_7	4.59	73.5	26.5	0.09
BP_8	0.9	83.5	16.5	0.10
BP_9	1.6	70.5	29.5	0.13
BP_10	7	57.9	42.1	0.35
BP_11	3.5	61.7	38.3	0.12
BP_12	1.5	60.9	39.1	0.13
BP_13	1.62	88	12	0.13
BP_14	5.5	60.5	39.5	0.16

Tabl. 4 - Results of bed load samples – Second Campaign

SAMPLE NUMBER	DEPTH (m)	clay and silt (%)	sand (%)	D_{50} OF SAND FRACTION (mm)
B1	2.56	14.5	85.5	2.50
B2	3.31	1.7	98.3	0.97
B3	4.55	54.9	45.1	0.26
B4	3.21	56.3	43.7	0.21
B5	7.7	36	64	0.16
BB1	3.6	16.7	83.3	0.60
BB2	4.86	3	97	1.15
BB3	6.8	25.9	74.1	0.22
BB4	4.6	48.8	51.2	0.24
BB5	7.48	43	57	0.23

The sieving curves for all samples are presented in annex 2 and 3 respectively for the first campaign and the second campaign.

5.3. ANALYSIS

The results presented above show a clear pattern of sediment sorting in the reservoir: the sediment from the channel in the middle of the reservoir is sandy, while sediment on the banks is finer.

This is shown in the figures below which present the correlation between depth of the bed level and the amount of fine sediment (clay and silt) in the mixture.

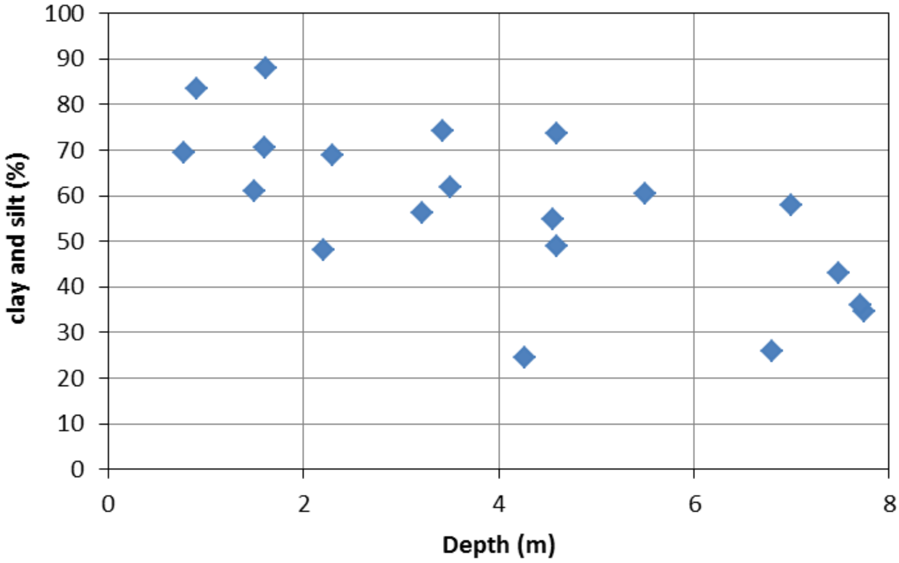

Fig. 16. Correlation between fraction of fine sediment and depth - samples in the reservoir from the two campaigns

The sieving curves presented in annex 2 and 3 indicate a clear sand mode in most samples. The D_{50} of this mode is very consistent between the different samples of the first campaign: except for BP_7 and BP_10, the D_{50} of all samples ranges between 0.11 and 0.17 mm (average 0.14 mm). The correlation between grain size and depth indicates that deeper sediment tends to be slightly coarser (see figure below), but this tendency is rather weak. For all samples from the first campaign except BP_10 the amount of coarse sand is negligible.

The second campaign includes samples upstream of the reservoir (B1, B2, BB1 and BB2). These samples indicate that the bed sediment there is much coarser, with a sand grain size of about 1 mm. The samples in the reservoir for the second campaign are also slightly coarser than the samples of the first campaign. The most probable reason for this coarsening is the flushing that happened on the 2nd of May (personal information from Rodrick Champiti).

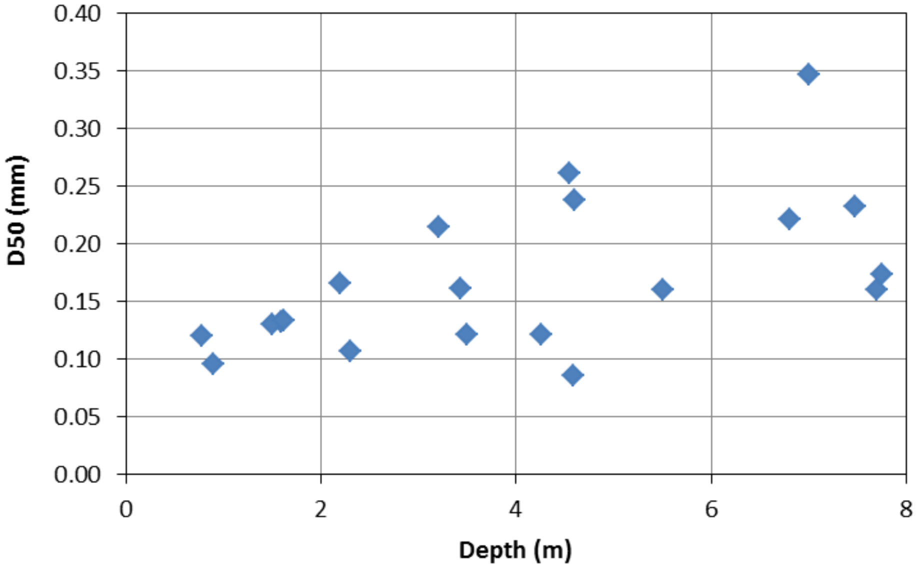

Fig. 17. **Correlation between median diameter of sand and depth**

The results of these two campaigns are in agreement with those presented in 5.1, which include samples from Nkula reservoir and Tedzani reservoir. The patterns of deposit seem very similar, with similar mixtures of clay, silt and sand, and a similar D_{50} for the sand mode. These other reservoirs in the Middle Shire, that are upstream of Kapichira, have also been built earlier (1967 for Nkula, 1973 for Tedzani). They probably have reached their bathymetric equilibrium profile and thus are no more an obstacle to bedload sediment transport. It is therefore normal that the same bed sediment is transported downstream to Kapichira reservoir.

5.4. FALL VELOCITY MEASUREMENT

For three bed load samples from the first campaign, a direct measurement of the distribution of the fall velocity of the sediment was performed. This method of measurement, called "Oden balance", consists in a settling tube at the bottom of which the weight of the sediment deposited is measured as a function of time.

The results are presented in the figure below.

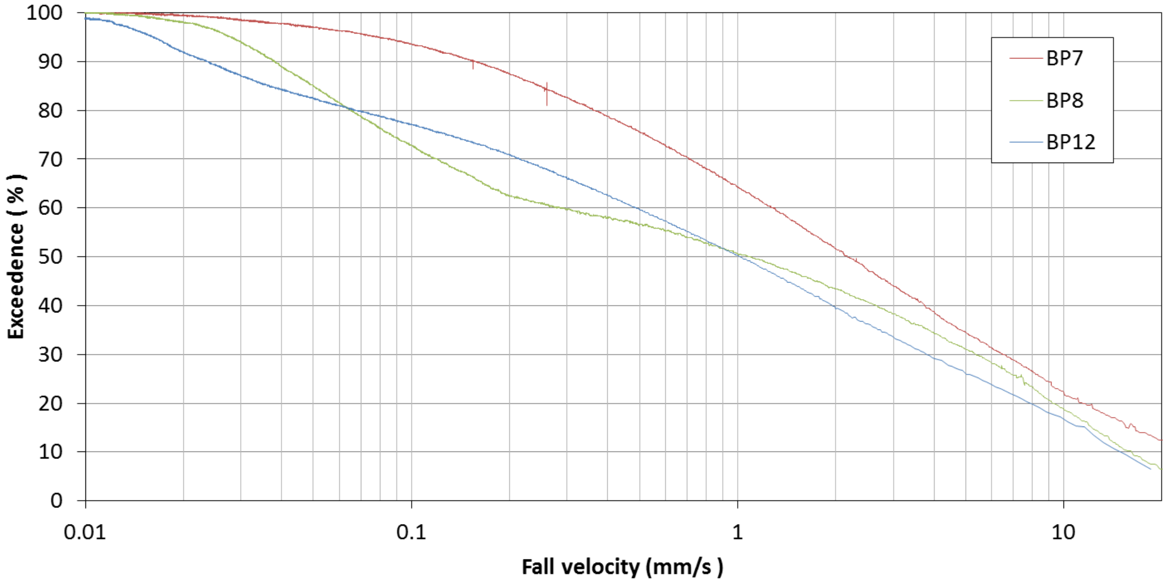

Fig. 18. ***Fall velocity distribution***

These results give an estimation of the size distribution of the fine fraction of the samples (as fall velocity is related to grain size), that could not be determined by sieving. There is no clear mode of fine sediment: for the three samples tested, there is a significant amount of fine, medium and coarse silt (fall velocity below 3 mm/s, grain size below 63 microns). Sample BP7 has very few clay and very fine silt (fall velocity below 0.06 mm/s, grain size below 8 microns), in contrast to samples BP8 and BP12 which have about 20% of this fine material. This indicates that this fine material is able to settle only in areas of very low velocity like BP8 and BP12.

6. CONCLUSION

This report has presented all the data that will be used in order to set-up and calibrate the numerical model of Kapichira reservoir. It includes pre-existing data as well as results of surveys performed specifically for this task: a bathymetric survey, and a sediment survey that consisted in both bed sediment survey and suspended sediment survey.

We present below an overview of all the pertinent data gathered, how they will be used for the modelling, and what is not fully known.

Bathymetry

The present topo-bathymetric state of the reservoir is well known from the recent survey. It will be used for calibration of the numerical model on the observed morphological evolution of the reservoir since its building. It will also be the reference state of the numerical model, based on which different configurations of the water intake will be tested.

This initial bathymetry of the reservoir is also well known (except in the upstream end of the reservoir). This will be used as the initial state of the numerical model for the morphological calibration.

Hydrology

The times-series of incoming Shire river discharge in the reservoir since the building of the dam has been constructed from the available data. It will be used for the calibration on the observed morphological evolution, and will also enable to define representative hydrological scenarios for testing different intake configurations.

The operation of the dam by ESCOM is known in general, although some details are lacking. In particular the exact criterion for the value of the environmental flow (through the spillways) is not known. The hypotheses used in the numerical model for the operation of the flushings have been inferred from the flushing events that took place during the period of the dataset provided by ESCOM.

Sediment

The composition of the sediment deposits in the reservoir has been well identified, with mostly sand in the main channel, and fine sediment on the top of the side banks. As it has not been possible to perform a survey when water was low in the reservoir, the composition of the sediment below the bed surface is not known.

The range of suspended sediment concentration (SSC) entering the reservoir is rather well determined, as the values of SSC measured during the first campaign are in accordance with former surveys from the literature. There remains some uncertainty on the SSC happening during floods, as the only measurements available in these conditions date from 1991. In the dry season, SSC is obviously low, and our measurements, performed early in the dry season, probably give a maximum of the SSC value that might be encountered during this season.

The ability of the reservoir to erode its sediment deposits, either during floods or during flushings, could not be investigated. Unfortunately, we could not perform a survey during flushing that would have enabled us to assess the efficiency of these events.

As a conclusion, although some uncertainties remain, this dataset is still rather complete. In particular, all the data necessary to perform a calibration of the numerical model on the long-term morphological evolution of the reservoir are available. This calibration of the model is the most significant and will ensure that the numerical model is representative of the real sediment transport processes in the reservoir.

ANNEXE 1

BATHYMETRIC DATA

ANNEXE 2
BED-LOAD DATA (1ST CAMPAIGN)

ANNEXE 3
BED-LOAD DATA (2ND CAMPAIGN)